AD-A258 727

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
FINAL 1 Oct 88 - 30 Sep 92

4. TITLE AND SUBTITLE
"HIGHER ORDER CROSSINGS"(U)

5. FUNDING NUMBERS
61102F
2304/A5

(2)

6. AUTHOR(S)
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AFOSR-TR- 92 0953

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NM
Bldg 410
Bolling AFB DC 20332-6448

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFOSR-89-0049

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
Distribution unlimited

12b. DISTRIBUTION CODE
UL

13. ABSTRACT *(Maximum 200 words)*

In the research on higher order crossings (HOC) they have solved some of the mathematical/statistical problems associated with a certain contraction mapping method for frequency detection and estimation in the presence of noise. They can now tell how to shrink the filters bandwidth to achieve almost sure convergence of the HOC sequence. The sample first order autocorrelation in filtered data is called a higher order correlation, or HOC again. Given the close association between the two types of HOC, these two types of HOC are in fact equivalent under some conditions the nonlinear least squares precision using O(N) computational complexity, but without any matrix inversion and/or other complicated calculations.

14. SUBJECT TERMS

15. NUMBER OF PAGES
8

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

September 1992

FINAL REPORT FOR 10.1.90–9.30.92

HIGHER ORDER CROSSINGS

Grant AFSOR-89-0049

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1 Work on Parametric Filtering

As related in our last progress report, in the research on higher order crossings (HOC) we have solved some of the mathematical/statistical problems associated with a certain contraction mapping method for frequency detection and estimation. This method shows how to fine tune a family of parametric filters for the purpose of frequency location and estimation in the presence of noise. We can now tell how to shrink the filters bandwidth to achieve almost sure convergence of the HOC sequence.

The sample first order autocorrelation in filtered data is called a higher order correlation, or HOC again. Given the close association between the two types of HOC, these two types of HOC are in fact equivalent under some conditions. Using HOC from correlations, we can show that the CM method approaches under some conditions the nonlinear least squares precision using $O(N)$ computational complexity, but without any matrix inversion and/or other complicated calculations.

1.1 From HK to CM

The present Principal Investigator has initiated the study of tuning parametric filters by higher order crossings (HOC) which are zero-crossing counts in filtered time series. The original work led to the development of the He-Kedem algorithm (HK) published in *IEEE TR Infor. Th.*, 35, 1989, pp. 360-370. Subsequently, the work has been extended substantially in the work of the Principal Investigator together with his collaborators S. Yakowitz and T. Li.

Specifically, in "On the contraction mapping method for frequency estimation," SRC Report TR 92-45, we proved the strong consistency of the HK method when the filters are band pass filters which satisfy a certain basic property. As such (i.e. with band pass filters) the method is called the *Contraction Mapping Method* or CM. In "Practical aspects of a fast algorithm for frequency detection." To appear in *IEEE Tr. on Communications*, we have shown that CM is *fast* and performs well as compared with other fast methods. In both works, a main idea is to enhance the speed of convergence by bandwidth shrinkage. In a sequence of Systems Research Center reports–see description below–it was shown that with a particular parametrization of the AR(2) filter it is possible to approach the precision of nonlinear least squares but with much less computation.

1.2 From CM to AR

The idea of HOC can be extended by combining the AR method for frequency estimation with parametric filters. This has been done in the work "Improving Prony's estimator for multiple frequency estimation by a general method of parametric filtering," (submitted), and in the Ph.D. thesis of T. Li "Multiple Frequency Estimation in Mixed-Spectrum Time Series by Parametric Filtering," SRC Ph.D 92-7. When the noise is white, the new hybrid can separate two very closely spaced frequencies.

1.3 Fixed Points

Our contraction mappings converge to certain fixed points which are precisely the cosine of the frequencies to be detected. We can converge to a particular fixed point by adjusting the filter parameter and shrinking the bandwidth iteratively. Or, we can obtain a sequence of converging fixed points. This is explained in our work (together with S. Lopes) "Fixed points in mixed spectrum analysis," in *Probabilistic and Stochastic Methods in Analysis, With Applications*, J.S. Byrnes et al. (eds), 1992, pp. 573-591, Kluwer, Norwell, Mass.

2 Basic Results in Stationary Processes

Our work has led us to consider some basic problems in the theory of stationary processes.

2.1 Ergodicity Of the Zero-Crossing Rate

We have shown that [illegible]ssing rate of a zero-mean stationary process does not converge to [illegible] the case of a mixed spectrum with at least two atoms. It does [illegible]wever for a sinusoid plus noise when both the sine and the noise [illegible] same *first order* autocorrelation. It turns out that this is precisely [illegible] the CM method, as the method converges. This is yet another [illegible] of the algorithm from an unexpected angle.

This work is reported in "On autocorrelation estimation in mixed spectrum Gaussian processes," (submitted) with E. Slud.

2.2 Effect of Filter on Zero-Crossings

If you aplly a high pass filter to a stationary time series, can you expect more zero-crossings on the average ? We can only answer this basic question when there is an expression relating the first order autocorrelation and the zero-crossing rate. This is established in " Monotone Gain, First-Order Autocorrelation, and Expected Zero-Crossing Rate," (with T. Li) *Annals of Statistics*, 19, pp. 1672-1676, 1991.

2.3 Extension of Rice's Formula

We have (with J. Barnett) devised a method for finding the expected number of zero-crossings of monotone functions of zero mean stationary Gaussian processes. Our formula extends Rice's formula derived in 1944. Our result is reported in "Zero-crossing rates of functions of Gaussian processes," *IEEE Transactions on Information Theory*, 37, pp. 1188-1194, 1991.

3 Estimation in PC Processes

Periodically correlated processes display a period T in the mean and in both arguments of the covariance function. The process is nonstationary, and its spectrum concentrates along $2T - 1$ diagonal lines. The estimation of the period is an extremely tricky business. This problem has been considered in "Estimation of the period of periodically correlated sequences," (with D. Martin), to appear in *Jour. of Time Series.*

4 Nondestructive Testing

We have helped in the application of HOC in nondestructive testing and evaluation of aluminum and composite joints. There is a sequence of about 20 papers by P. Dickstein, University of Toronto, that describes this application.

5 Publications

5.1 Papers in Journals and Proceedings

1. "Zero-crossing rates of functions of Gaussian processes," (With J. Barnett) *IEEE Transactions on Information Theory*, Vol. 37, pp. 1188-1194, 1991

2. "Elliptically symmetric orthant probabilities," *American Statistician*, 45, p. 256, September, 1991.

3. " Monotone Gain, First-Order Autocorrelation, and Expected Zero-Crossing Rate," (With T. Li) *Annals of Statistics*, 19, pp. 1672-1676, 1991.

4. "Fixed points in mixed spectrum analysis," (With S. Lopes) to appear in proceedings of NATO ASI, Il Ciocco, Italy, July 1991.

5. "Contraction mappings in mixed spectrum estimation." To appear in an IMA Springer Verlag volume. *IEEE Transactions on Information Theory*, Vol. 37, pp. 1177-1188.

6. "Estimation of the period of periodically correlated sequences," (with D. Martin). To appear in *Jour. of Time Series.*

7. "Practical aspects of a fast algorithm for frequency detection," (With S. Yakowitz). To appear in *IEEE Tr. on Communications.*

8. "Optimal thresholds for the estimation of area rain rate moments by the threshold method," (with D. Short and K. Shimizu). To appear in *Jour. of Applied Meteorology.*

5.2 Submitted Papers

1 Kedem, B. and E. Slud, "On autocorrelation estimation in mixed spectrum Gaussian processes," submitted (1991).

2. Kedem, B. and E. Slud, "Partial likelihood analysis of logistic regression and autoregression," submitted (1991).

3. Kedem, B. and S. Yakowitz, "A Contribution to Frequency Detection," (being revised for IEEE Tr. Communication) (1990).

4. Kedem, B. and S. Yakowitz, "On the contraction mapping method for frequency estimation," submitted (1991).

5. Li, T. and B. Kedem, "Asymptotic properties of the contraction mapping method for frequency estimation," submitted (1991).

6. Li, T., B. Kedem, and S. Yakowitz, "Asymptotic normality of the contraction mapping estimator for frequency estimation," submitted (1991).

7. Lopes, S. and B. Kedem, "Spectrum analysis in FM sinusoidal models," submitted (1992).

8. Li, T. and B. Kedem, Improving Prony's estimator for multiple frequency estimation by a general method of parametric filtering," submitted, 1992.

5.3 Technical Reports

1. "Strong consistency of the contraction mapping method for frequency estimation," (with T. Li), Tr. 92-21

2. "Asymptotic normality of the contraction mapping estimator for frequency estimation," (with T. Li and S. Yakowitz), TR-92-22

3. "On the contraction mapping method for frequency detection," (with S. Yakowitz), TR 92-15

4. "Estimation of Multiple sinusoids by parametric filtering," (with T. Li), TR 92-51

5. "Multiple Frequency Estimation in Mixed-Spectrum Time Series by Parametric Filtering," (Ph.D Thesis, T. Li Report 92-7 SRC)

6 Invited Presentations

1. "Threshold method," Statistics and Probability Day, GWU, October 20, 1990.

2. "Contraction mappings in spectrum analysis," AT&T Bell Labs, Murray Hill, NJ, October 26, 1990.

3. "Higher order crossings," Sequence of lectures on HOC, Tsinghua University, Beijing, PRC, Dec. 22, 1990- Jan. 10, 1991.

4. "Contraction mappings in spectrum analysis," Dynamics Seminar, Mathematics Dept., UOM, Feb. 7, 1991.

5. "Size distributions," Discussant, WSS, DC, January 16, 1991.

6. "HK Algorithm," USAF, Rome Air Development Center, NY, June 18-19, 1991.

7. "Fixed points in mixed spectrum estimation," NATO ASI, IL Ciocco, Italy, July 14-27 1991.

8. "Threshold method, Statistics Colloquium," Toronto University, Toronto, Canada, September 27, 1991.

9. "Higher order crossings," Washington Stat. Society. and GWU, October 10, 1991.

10. "Threshold method" Statistics Colloquium, UMBC, Catonsville, MD November 22, 1991

11. "Optimal Thresholds for Rainfall Measurement From Space," Wayne State, Detroit, Feb. 11, 1992.

11. "Optimal Thresholds for Rainfall Measurement From Space," University of Connecticut, Storrs, CT, March 19, 1992.

12. "Prediction of Level Exceedances ," Systems Research Center, UOM, April 3, 1992.

13. "A sinusoidal Limit, Harmonic Analysis Seminar," University of Maryland, Math. Dept., April 8, 1992.

14. "A Challenge of a NASA Earth Probe Mission: How to Measure Rainfall From Satellites When You Can't...," Undergraduate Math Colloquium, April 29, 1992.

15. "Improving the AR approach of frequency estimation by parametric filtering," (with T. Li), Penn State, May 6, 1992.

15. 1. "Partial likelihood analysis of logistic regression for dependent data," Santaiago de Compostela, Spain, June 30, 1992. 2. "Contraction Mappings in Frequency Estimation," Santaiago de Compostela, Spain, July 2, 1992.

16. "Amending the AR Method for Frequency Detection by Parametric Filtering," Technion, Israel, July 14, 1992.

7 Workshop

Our research was presented in a special workshop titled "*SIGNAL PROCESSING BY ZERO-CROSSINGS*," held at Mathematics Department, University of Maryland, College Park, on March 4, 1992.

8 Honors/Awards/Prizes

1. B. Kedem, Visit[illegible] [illegible]tems Research Center, University of Maryland, 1991-3.

2. B. Kedem was in[illegible] [illegible]ghua University, Beijing, China, to give a sequence of lect[illegible] [illegible], Dec. 22, 1990-Jan. 10, 1991.

9 Ph.D.'s

1. Martin, D.E.K. (1990). *Estimation of the minimal period of periodically correlated sequences.*
2. Lopes, S. (1991). *Spectral analysis in frequency modulated models.*
3. Pavlopoulos, H. (1991). *Statistical inference for optimal thresholds.*
4. Troendle, J.F. (1991). *An iterative filtering method of frequency detection in a mixed spectrum model.*
5. Li, T. (1992). *Multiple frequency estimation in mixed-spectrum time series by parametric filtering.*

10 Application of HOC in nondestructive testing

This research was influenced by the principal investigator through conversations and papers. The methodology is used in testing the adhesion of composites and aluminum joints. The main trick is to use the ψ^2 statistic as a distance from white noise. Some of this work was reported in the March 4 workshop mentioned above.

1. Dickstein, P.A., J.K. Spelt, and A.N. Sinclair. "Application of a higher order crossing feature to non-destructive evaluation: a sample demonstration of sensitivity to the condition of adhesive joints," *Ultrasonics*, 29, pp. 355-365, September 1991.
2. Dickstein, P.A., J.K. Spelt, A.N. Sinclair, and Y. Bushlin. "Investigation of nondestructive monitoring of the environmental degradation of structural adhesive joints," *Materials Evaluation*, pp. 1498-1505, December, 1991.